Appendix

8 Changes to cloudy

Implementation

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Abstract — In this chapter a full description of the new or changed commands in CLOUDY will be given. Also the changes to the output will be described and a full list of the emission lines that were added will be given. It is assumed that the reader is familiar with HAZY, the original documentation of CLOUDY written by Gary Ferland.

8.1 New and changed cloudy commands

In the following sections a structure will be used which adheres as much as possible to the structure of the original documentation HAZY, i.e. first the new and changed commands will be described, then the changes to the output of CLOUDY will be described and finally all the emission lines that have been added to the code will be listed.

distance 21.85 [linear; parsec; vary]

You can supply the distance between the object and the observer to CLOUDY. This distance is used to normalize the flux emitted by the object at the earth's distance and to calculate the angular diameter. The number supplied should be the logarithm of the distance in centimeter. If the keyword PARSEC appears on the line, the number will be interpreted as the logarithm of the distance in parsec. If the keyword LINEAR appears, the number will be taken to be linear. The default distance is 1 kpc.

The distance can be varied by the optimizer if the keyword VARY appears on the line. Note that this only makes sense if distant dependent observables are supplied (like absolute fluxes or the angular diameter).

dlaw 3.80 −2 [vary]

This command allows you to define a special density law: the density is assumed to be constant inside the Strömgren radius, and the density will change according to an r^{α}-law outside the Strömgren radius. You need to supply two numbers: the logarithm of the number density per centimeter cubed in the constant density part, and the exponent α. Note that the two sections of the density law will be joined continuously at the Strömgren radius.

An optional keyword can be supplied to vary the density (i.e. the first number on the input line).

dtable [use full range]

This command allows you to supply an arbitrary density law in a separate file. This file should have the name `dens_law`. It should consist of an arbitrary number of lines (not more than 1000) each containing two numbers: the logarithm of the radius in centimeter and the logarithm of the number density per centimeter cubed. CLOUDY will determine the density at each radius by linear interpolation in this array. If an attempt is made to use a radius which is outside the range supplied in `dens_law`, a caution will be given in the output. The density at the nearest edge of the supplied range will be used. The radii supplied in `dens_law` should be strictly monotonically increasing.

If the keyword FULL appears on the line, the inner and outer radius of the nebula will be set to the complete range for which the density law is defined. This keyword can be used instead of the RADIUS command. A RADIUS command given further on in the input file will overrule the settings from this keyword.

element helium, carbon, . . . 11.02 [vary]

This command allows you to set the abundance of a single element, by giving it's usual name and the standard logarithmic notation for the abundance ($\epsilon(\mathrm{H}) \equiv 12$). This

command also allows you to vary the abundances for each element separately.

flunit herz, jansky, nuFnu, . . . [at earth distance].

With this command you can change the unit and the normalization of the continuum flux in the PLOT CONTINUUM and the PLOT EXTENDED SPECTRUM commands.

If the keyword EARTH appears on the line then the fluxes will be normalized at the earth's distance (or the default 1 kpc), otherwise at the inner radius of the nebula. If one of the keywords HERZ, Hz, CM-1 or JANSKY appears on the line, F_ν will be given in units of erg cm^{-2} s^{-1} Hz^{-1}, erg cm^{-2} s^{-1} (cm^{-1})$^{-1}$ or in jansky. Default is to give F_ν in units of erg cm^{-2} s^{-1} Ryd^{-1}. If one of the keywords MICRON or ANGSTROM appears on the line, F_λ will be given in units of erg cm^{-2} s^{-1} μm^{-1} or erg cm^{-2} s^{-1} Å^{-1}. If the keyword NUFNU or LAFLA appears on the line, νF_ν or λF_λ will be plotted in units of erg cm^{-2} s^{-1}.

frunit Rydberg, Hz, micron, . . .

If you use the plot command to plot some quantity as a function of energy (or wavelength, or frequency) you can choose your preferred axis unit with this command. The possibilities are: RYDBERG, HZ or HERZ, CM–1, EV, ERG, MICRON, NM or NANOMETER and ANGSTROM.

grains [0.2; planetary, . . . ; _log; vary; . . .]

It is now possible to optimize the dust to gas ratio by adding the keyword VARY on the input line. For this the syntax of the command had to be extended slightly. If somewhere on the line the keyword _LOG appears, the number will always be interpreted as a logarithm no matter what the sign of this number is. The rest of the syntax of this command is kept fully compatible with the original command.

minimum electron temperature [10 K]

If you want to calculate a model of a nebula containing dust, and you want to get the far-IR continuum right, you need to integrate deep into the neutral zone of the nebula. Only there will the temperature of the dust drop to low enough values (say less than roughly 25 K), that the contribution of the dust emission to the total continuum will be negligible. The dust and the electron gas are usually not in temperature equilibrium in these regions. The electron gas will have lower temperatures than the dust, and the electron temperature can drop well below 10 K. For such low temperatures CLOUDY is not numerically stable anymore and can easily crash. You can solve this problem by using the MINIMUM ELECTRON TEMPERATURE command. This will cause the code to force the electron temperature to the prescribed minimum value, once it tries to drop below this. A value of 10 K is probably a good choice and is also the standard value.

Since the electron temperature will be forced to a higher than equilibrium value, there will be a heating-cooling mismatch in each zone were this command is effective. If there are sufficient of such zones present in the model, this will cause the overall heating and cooling for the model to be mismatched as well. CLOUDY will inform you about this. Usually this will not be a problem, you should however check if the discrepancy between heating and cooling is small with respect to the total energy emitted.

optimize amoeba

This command already existed in the original version of CLOUDY. However, since AMOEBA was the standard optimizing algorithm in the original version, it had no effect. In the modified version of CLOUDY however, the standard optimizing algorithm is PHYMIR. Hence, if one wants to use the AMOEBA algorithm, this command is compulsory now.

optimize angular diameter [<] 12″ [error 0.20]

It is possible to add an angular diameter in arcseconds to the list of observables. The program can try to optimize the distance and/or the radius of the nebula to reproduce this angular diameter. The radius of the nebula is defined as the Strömgren radius (i.e. this method is valid for diameters observed in radiation coming from the ionized part of the gas such as radio emission). The Strömgren radius is defined as the radius where the electron density drops below 10 % of the hydrogen density, or the outer edge of the nebula for density bounded nebulae. The error in the angular diameter is a linear relative fraction. It is also possible to supply an upper limit for the angular diameter.

optimize color temperature [<] 173 K [error 0.10]

With this command you can supply the color temperature of the dust continuum (e.g. obtained from a blackbody fit to the *IRAS* fluxes). The value needs to be a linear number in kelvin. The error is a linear relative fraction. It is also possible to supply an upper limit for the color temperature.

optimize continue

When using AMOEBA to optimize certain parameters, every couple of iterations the code will write a continue file which contains all information needed to restart from where the code is at that moment. When an optimization run stops this file can be used to restart the optimization process. All you need to do is:

1. include the command OPTIMIZE CONTINUE in the input file
2. edit other lines in the input file as needed, e.g. increase the maximum number of iterations in the OPTIMIZE ITERATIONS command. The initial values for the parameters to be varied in the input file need not be changed, they are ignored
3. make sure the continue file `fort.9` or `ftn09` is in place
4. start the run like any other run

As an alternative you can also use the macro CNTCL to execute these steps.

optimize far-infrared flux [<] 53.2 [error 0.10]

This command allows you to optimize the total infrared flux, normalized at the earth's distance, e.g. as determined from a blackbody fit to the *IRAS* fluxes. The distance to the earth is set by the DISTANCE command. The value should be entered as a linear number in units of 10^{-13} W m^{-2}. The error is a linear relative fraction. The total infrared flux is calculated as the integral from 1 μm to 300 μm over the emitted continuum of the nebula and includes internal extinction effects. Line emission in this wavelength region is not included in the integral. It is also possible to supply an upper limit for the total infrared flux.

This command, combined with the OPTIMIZE COLOR TEMPERATURE command, allows you to use an alternative for fitting the individual *IRAS* fluxes. Optimizing the latter sometimes causes problems when the abundances are varied. Since line contribution is included in the individual *IRAS* bands, the optimizing routine has two ways to achieve a better fit to the *IRAS* fluxes: by changing the continuum and by changing the line contribution through changing the abundances. The latter approach can lead to unrealistically high abundances. There is no way to control this behavior except by putting a stringent upper limit to the abundances, which is probably not what you want. In such cases, this command can be used as an alternative. Another alternative is to use the OPTIMIZE FLUX command. In this case the quoted fluxes in the *IRAS* bands should be converted into continuum fluxes using the appropriate color correction factors. This way the implicit assumption is made that the contribution of the line emission to these fluxes is negligible. At this moment it is not clear which approach is the best one.

optimize flux 3 _cm_ [<] 0.84 _mJy [error 0.15]

It is possible to optimize continuum fluxes at any wavelength within the extended range that is computed by CLOUDY (i.e. radio wavelengths are allowed). The wavelength should be linear and can be given in the units _CM_, MICRON, _NM_ or ANGSTROM. The fluxes should also be linear and can be given in _MJY, _JY_ or JANSKY. They are always assumed to be normalized at the earth's distance. The error is a linear relative fraction. It is also possible to supply an upper limit for the flux.

optimize intensity −12.20 [error 0.15]

This optimize command now computes and compares the flux of the reference line (usually Hβ) at the earth's distance instead of the inner radius of the nebula. The value should be the logarithm of the flux in units of erg cm^{-2} s^{-1}. The flux should be dereddened. The error is a linear relative fraction.

optimize lines
IRAS 60 [<] 23.00 linear jansky [error 0.10]

The limit on the maximum number of lines that you can supply has been increased from 100 to 200.

It is possible to add broadband photometry to the list of observed line intensities. You can supply the photometric flux in magnitudes (if the keyword _MAG appears on the line) or in jansky (if the keyword JANSKY appears). If the keyword JANSKY is used the number will be interpreted as a logarithm unless the keyword LINEAR is used. The syntax of the input line, apart from the keywords _MAG, JANSKY and LINEAR, is identical to the syntax for supplying an observed emission line ratio. The conversion between magnitudes and fluxes is defined such that the flux will be equal to the monochromatic flux at the effective wavelength of the filter pass band for a spectrum $F_\nu \sim \nu^{-1}$. The error is a linear relative fraction. It is also possible to supply an upper limit for the flux.

The list of supported photometric bands can be found in Table 8.1. Note that the fluxes are normalized at the earth's distance (or the default 1 kpc).

Table 8.1 — *List of the supported photometric systems.*

name		description	name		description
gnU	3464	Geneva *U*	JoL1	354	Johnson *L1*
gnB	4227	Geneva *B*	JoL2	344	Johnson *L2*
gnV	5488	Geneva *V*	Jo M	503	Johnson *M*
gnB1	4015	Geneva *B1*	Jo N	1067	Johnson *N*
gnB2	4476	Geneva *B2*			
gnV1	5395	Geneva *V1*	Be U	3764	Bessell *U*
gnG	5807	Geneva *G*	Be B	4416	Bessell *B*
			Be V	5505	Bessell *V*
st u	3451	Strömgren *u*	Be R	6395	Bessell *R*
st v	4108	Strömgren *v*	Be I	7854	Bessell *I*
st b	4671	Strömgren *b*	esJ	129	ESO *J*
st y	5477	Strömgren *y*	esH	165	ESO *H*
			esK	220	ESO *K*
Jo U	3574	Johnson *U*	esL'	381	ESO *L'*
Jo B	4466	Johnson *B*			
Jo V	5553	Johnson *V*	IRAS	12	*IRAS* 12 μm
Jo R	6939	Johnson *R*	IRAS	25	*IRAS* 25 μm
Jo I	8780	Johnson *I*	IRAS	60	*IRAS* 60 μm
Jo J	125	Johnson *J*	IRAS	100	*IRAS* 100 μm
Jo K	220	Johnson *K*			

optimize phymir

With this command you can use the new parallel optimization algorithm, especially designed for the Cray or other multi-processor computers. This algorithm is currently the standard, so this command does not have any real effect.

optimize tolerance 0.02

With this command it is possible to set the accuracy with which you want to determine the model parameters when optimizing. The number entered is the accuracy in dex in the logarithm of the parameter.

The algorithm will try to find a minimum within the requested accuracy (which is reached when the biggest

dimension of the search area is smaller than the requested accuracy). It will then try to check if this minimum really is the correct minimum. If it fails this test, the search process will be restarted, otherwise the final model will be printed.

plot opacity, . . .

The plot commands present in the standard release of CLOUDY (which give lineprinter plots) have been deleted. Instead a whole series of new plot commands aimed for use with the IDL routine PLC have been added. The total list of possible plot commands follows closely the list of punch commands. Some punch commands have no equivalent plot command because it would not be useful and some punch commands have been slightly altered (most notably the PLOT *element* OPACITY command will not terminate the program). The total list of plot keywords can be found in Table 8.2. For a description of the new plot command PLOT EXTENDED SPECTRUM, see below under the header PUNCH EXTENDED SPECTRUM. A combined maximum of ten plot and/or punch commands is permitted for each run.

print verbose, punch continuum verbose

When CLOUDY calculates a single model, it usually requires several iterations to reach the final model (see the ITERATE command). In the standard release of CLOUDY, printing, punching and plotting is done on each of these iterations, unless specified differently (e.g. with the PRINT LAST command).

In the current installation this situation has been reversed. The default is to give output only for the final iteration. You can change this by giving the command PRINT VERBOSE. You can combine this command with other print commands (e.g. PRINT EVERY 10 VERBOSE). For punching you must combine the keyword VERBOSE with some command, e.g. PUNCH CONTINUUM VERBOSE. Note that this keyword acts for punching and plotting commands simultaneously. It should also be noted that with this keyword the resulting output for plot commands can not be processed with the standard macros to produce a plot file.

punch emissivity unit=20 freq=0.00452 Ryd

This command will write the volume emissivity j_ν and the absorption coefficient κ_ν as a function of radius for the computed model. The frequency should be a linear number in Rydberg, and can take any value within the extended frequency range of CLOUDY (i.e. it may also be in the radio continuum). At the moment it is unfortunately mandatory that the logical unit number is specified before the frequency. This requirement may be relieved in the future. The output of this command can be used for any external code solving the radiative transport equation, e.g. to obtain a two-dimensional solution.

The first line in the punch file is a comment line, stating the requested frequency. The second line gives the inner radius of the nebula in cm and the stellar flux in Ryd $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{Ryd}^{-1}$ normalized at the inner radius. From the third line onwards each line gives the radius of the center of the zone in centimeter, the volume emissivity in Ryd $\mathrm{cm}^{-3}\,\mathrm{s}^{-1}\,\mathrm{Ryd}^{-1}$ and the absorption coefficient in cm^{-1} for each zone of the model. The last line of the punch file gives the Strömgren radius in centimeter, the total optical depth at the requested frequency (from the center of the nebula to the outer edge), and the distance of the nebula in centimeter.

punch extended spectrum [jansky]

This additional punch command will punch the flux of the extended continuum in erg $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{Hz}^{-1}$ normalized at the inner radius of the cloud. The frequency will be given in Rydberg. When the corresponding plot command is used, the flux unit can be chosen with the FLUNIT command, and the frequency unit with the FRUNIT command. Additionally, the volume emissivity (in photons $\mathrm{cm}^{-3}\,\mathrm{Ryd}^{-1}$), the absorption coefficients (in cm^{-1}) and the source function (in photons $\mathrm{cm}^{-2}\,\mathrm{Ryd}^{-1}$) will be given. These quantities pertain to the outermost zone. The fifth quantity that will be given is the total optical depth as function of frequency (from the center of the nebula to the outer edge). The extended continuum is the normal continuum calculated by CLOUDY combined with the radio continuum. It extends out to a wavelength of 3.04 m, instead of the 0.911 cm used in the standard release.

rfac 3. vary

This command is an addition to the RADIUS command. The number on the line is the ratio of the outer to the inner radius. The number is interpreted as a logarithm when ≤ 1 or when the keyword _LOG is present, else as a linear quantity. Values ≤ 0 are illegal.

The ratio can be varied if the keyword VARY appears on the line. This then gives you the possibility to optimize both the inner and outer radius of a shell, if you use this command together with the RADIUS . . . VARY command. Other combinations are also possible, e.g. to vary the inner radius while keeping the ratio of the outer to inner radius fixed.

runit parsec, cm, A_V

With this command you can set the unit for the radius in a plot. Default is to use centimeters. If the keyword PARSEC or PC occurs on the line, then parsecs will be used. If the keyword ARCSEC occurs on the line, then arcseconds will be used. This is only meaningful when the distance is set with the DISTANCE command. If the keyword A_V is used, then A_V will be used instead of the radius. This choice has the additional side-effect that the radius will be plotted against A_V, instead of the reverse in the PLOT _PDR command.

set drmax 0.01 relative

This command is a variation of the standard SET DRMAX command. It allows you to specify the maximum zone thickness as a fraction of the current radius. This makes

Table 8.2 — *List of the plot commands. The first column gives the name of the plot command. The second column gives the quantities that are being plotted.*

keyword	plotted quantities
opacity	albedo; total, absorption and scattering opacity
grain opacity	albedo; total, absorption and scattering opacity (grains only)
carbon,... opacity	photo-ionization cross section for an arbitrary element heavier than helium
hydrogen,...	ionization structure for an arbitrary element
compton	Compton heating and cooling
continuum	incident, attenuated incident, diffuse, transmitted, reflected
extended spectrum	continuum, emis. & abs. coefficient, source function, opt. depth
gaunt factors	free-free Gaunt factors for hydrogen and helium
grain physics	temperature, potential, drift velocity per species; tot. heating, cooling
line structure	volume emissivity for requested lines
line cumulative [relative]	integrated line strength [relative to norm line] for requested lines
Lyman alpha	optical depth, level population, excitation temp, electron temp
_map	total heating and cooling as function of electron temperature
molecules	relative molecule density
optical depths	total, absorption, reflection optical depths
_ots continua	flux, otscon, otslin, outcon
_pdr	photo-dissociation region physics
physical conditions	electron temp, hydrogen dens, electron dens, heating, acceleration
pressure	gas, line, continuum pressure
_qs	absorption and scattering efficiency for grains
radius	radius, zone thickness as function of zone number
recombination efficiency	τ_{912}, recombination efficiency to H(n=1), loss probability
source function	emission, absorption coefficient, source function, Planck ratio
temperature	electron temperature, gradient of electron temperature
wind structure	velocity, acceleration, force multiplier

the command also useful for very thick nebulae, since the maximum zone thickness will increase as the code moves through the nebula. The fraction should be given as a linear number. Values ≤ 0 and ≥ 1 are forbidden. This command is recommended when doing optimizer runs. The value of 0.01 given above should normally be a good choice.

silent

With this command all intermediate output of the optimizer is disabled, i.e. only the initial messages and the final model are displayed. This is useful for preventing very large output files which might not fit on your disk.

single iteration

If you are doing optimizer runs, you are sometimes interested in doing single iterations by hand. If this command appears somewhere in the input file, the run will be started just like a normal optimizer run but will be stopped after just one iteration. It differs from the NO VARY command in that the χ^2 section of the output will be printed.

stop flux at 5.9 _cm_ 93 _mJy

This command will cause the model to stop once a prescribed continuum flux is reached. The syntax for supplying the wavelength and flux is identical to the syntax for the OPTIMIZE FLUX command. See also the comments given under the header STOP PHOTOMETRY.

stop [ionized] mass 0.2 [solar]

This command will cause the model to stop once a prescribed ionized or total shell mass is reached. If the keyword SOLAR is present the mass should be given as a linear number in solar units, else the mass should be given as a logarithmic number in atomic units.

stop photometry IRAS 60 23.56 Jy [−2.32 magnitude]

This command will cause the model to stop once a prescribed flux in a certain photometric band is reached. You need to supply the flux as a linear number in jansky or, if the keyword MAGN is present, as a magnitude. You can use this command to determine the extent of the neutral zone, which usually can't be obtained directly from observations. Since the far-IR flux predominantly comes from the neutral region, a photometric band in this wavelength region like *IRAS* 60 μm or 100 μm would be suitable.

sublimation radius 17.25

When you calculate a model where the gas and dust is situated very close to the central star, this can result in the dust temperature to be unphysically high at the inner edge of the nebula. The code will complain about this, but will nevertheless include the emission from that dust in the emitted spectrum. You can prevent this by setting a separate inner radius for the dust shell. The number you give

should be the logarithm of the radius in centimeter. You can combine this command with the command SUBLIMATION TEMPERATURE. In this case, the resulting inner radius for the dust shell will be such that both conditions will be fulfilled there.

sublimation temperature [1000 K]

When you calculate a model where the gas and dust is situated very close to the central star, this can result in the dust temperature to be unphysically high at the inner edge of the nebula. To prevent this, the command SUBLIMATION TEMPERATURE can be used. This will cause the code to incorporate dust in the model only in those zones where an approximation to the dust temperature is below a prescribed equilibrium value. In the zones closer to the star, the dust is assumed to be absent, i.e. either no dust or the complete amount of dust is assumed to be present in any particular zone. The default value for the sublimation temperature is 1500 K, but this value can be changed by giving an alternative value on the command line. This sublimation temperature is valid for all requested grain species, i.e. it is not possible to request different temperatures for different species. You can combine this command with the command SUBLIMATION RADIUS. The resulting inner radius for the dust shell will be such that both conditions will be fulfilled there.

8.2 Changes to the output

8.2.1 Compilation identifier

The first line of the CLOUDY output section which repeats the input lines now contains a unique compilation identifier which looks something like `940331a`. Using this identifier the exact CLOUDY version and the machine it was compiled on can be reconstructed. You can check this in the file `$CLD_DOC/cloudy.log` where a log of all compilations and modifications to CLOUDY is kept.

8.2.2 Output units

In CLOUDY the default logical unit for the final optimizer output as well as the default starting number for the punch logical units is 7. However under HP/UX logical unit 7 is reserved as standard error output. Therefore in the current installation the default logical unit for the optimizer output has been changed to unit 2 and the default starting number for the punch logical units is now unit 10.

It should be noted that, in addition to the logical unit numbers already reserved in CLOUDY (units 5,6 as standard input & output units, 0 or 7 as standard error output and units 90 thru 99 for internal use), the logical units 1,3 and 80 thru 89 are reserved for the plot commands. This assignment can *not* be changed by giving an explicit unit number on the plot command line. Logical unit 9 is reserved for the continuation file written during an optimizer run. Logical units 4 and 8 are reserved for future use.

8.2.3 Output frequency

When CLOUDY calculates a single model, it usually requires several iterations to reach the final model (see the ITERATE command). In the standard release of CLOUDY, lineprinter output as well as punch output is produced on each of these iterations, unless stated otherwise (e.g. with PRINT LAST). In the current installation this situation has been reversed. The standard is to give output only in the last iteration, unless the keyword VERBOSE is given (see also Sect. 8.1).

It is possible now to give punch and/or plot commands in optimizer runs. Output will be generated only for the final model.

8.2.4 Additional model output

At the end of the lineprinter output (if the command PRINT SHORT was given), or just in front of the `Contin Optical Depths` section otherwise, the current installation of CLOUDY will generate some extra lines of output which are described here.

Line 1: nebular radii

On this line the inner and outer radius of the nebula are given, both logarithmic (in centimeter) and linear (in parsec). Also the linear ratio of the outer to inner radius is given.

Line 2: Strömgren radius, distance, nebular mass

On this line the Strömgren radius and the distance of the nebula are given, both logarithmic (in centimeter) and linear (in parsec or kiloparsec respectively). Subsequently the angular Strömgren diameter is given in arcsecond. Last, the total and ionized shell mass are given in solar units.

Line 3: mean atomic weight, dust/gas ratio, stellar magnitudes

On this line first the mean atomic weight per hydrogen nucleus in atomic units is given. Then the linear dust-to-gas mass ratio is given. Subsequently are listed the internal extinction A_V and the stellar magnitude m_V as seen through the nebula (i.e. reddened by internal extinction). Both numbers are in magnitudes. Last, the corresponding numbers for the Johnson *B* band are given.

Line 4: Zanstra temperature, excitation class

On this line both the hydrogen and helium Zanstra temperature are given. If no solution for the temperature could be found, zero will be given. Subsequently the excitation class for the nebula is given, using the formula given by Dopita & Meatheringham (1990).

Line 5: average Ne, emission measure

This line gives the average electron density for the model in cm^{-3}. The value is computed as

$$\overline{n_\mathrm{e}} = \int n_\mathrm{e}^3 \mathrm{d}V \Big/ \int n_\mathrm{e}^2 \mathrm{d}V.$$

The second number gives

$$\left(\overline{n_\mathrm{e}^2}\right)^{1/2} = \left(\int n_\mathrm{e}^4 \mathrm{d}V \Big/ \int n_\mathrm{e}^2 \mathrm{d}V\right)^{1/2}.$$

The third number gives the n^2 parameter, which is defined as

$$n^2 = \frac{\overline{n_\mathrm{e}^2} - \overline{n_\mathrm{e}}^2}{\overline{n_\mathrm{e}}^2}.$$

The last number is the logarithm of the emission measure $\int n_\mathrm{e}^2 \mathrm{d}V$ in cm^{-3}.

Line 6: average Te, absolute Hβ *flux*

This line gives the average electron temperature of the model in kelvin. The value is computed as

$$\overline{T_\mathrm{e}} = \int n_\mathrm{e}^2 T_\mathrm{e} \mathrm{d}V \Big/ \int n_\mathrm{e}^2 \mathrm{d}V.$$

The second number gives

$$\left(\overline{T_\mathrm{e}^2}\right)^{1/2} = \left(\int n_\mathrm{e}^2 T_\mathrm{e}^2 \mathrm{d}V \Big/ \int n_\mathrm{e}^2 \mathrm{d}V\right)^{1/2}.$$

The third number gives the t^2 parameter, which is defined as

$$t^2 = \frac{\overline{T_\mathrm{e}^2} - \overline{T_\mathrm{e}}^2}{\overline{T_\mathrm{e}}^2}.$$

The last number gives the logarithm of the absolute Hβ flux in erg $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ at the earth's distance. This flux is *not* reddened by internal extinction.

Line 7: far infrared flux, total flux in spectrum

On this line the total far infrared flux is given, defined as the integrated continuum flux from 1 μm to 300 μm, both as a logarithmic intensity (in erg per second) and a linear flux at the earth's distance (in 10^{-13} W m^{-2}). Subsequently the total intensity of the nebular continuum, the nebular lines and the sum of these two is given as a logarithm in erg per second.

Line 8: fitted far infrared flux

A blackbody fit to the computed *IRAS* fluxes is made, if dust is included in the model. From this fit the following parameters are calculated: the logarithm of the total intensity of the blackbody integrated over all wavelengths (in erg per second), the color temperature (in kelvin) and the blackbody fluxes at the *IRAS* central wavelengths (in jansky).

Line 9: infrared excess

On this line six numbers are given: the infrared excess computed from the total Lyα flux, the logarithm of the total Lyα flux, the infrared excess computed from the 6 cm radio flux by using a simple approximation and by using the full formula, the Y factor used in this formula and last, the infrared excess computed from the Hβ flux. The flux value is the logarithm of the flux in erg s^{-1} (closed geometry) or erg $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ (open geometry).

Note that both the 6 cm and the Hβ infrared excess use the Case B ratio of Lyα to Hβ. In CLOUDY this ratio is only valid at high densities ($> 10^4$ cm^{-3}).

Line 10 thru 13: radio fluxes

In four lines information is given about the radio free-free emission at the wavelengths of 2 cm, 3 cm, 6 cm and 20 cm. Each line gives the flux in milli-jansky, the optical depth τ of the nebula measured from the center of the nebula to the outer edge and the brightness temperature defined as $T_\mathrm{b} = \overline{T_\mathrm{e}}[1 - \exp(-\tau)]$. This last number will be wrong if the nebula is very optically thick at that wavelength ($\tau > 100$). This is because the continuum forming region then lies outside the Strömgren sphere, where the electron temperature is considerably lower than $\overline{T_\mathrm{e}}$. Under normal circumstances this will only happen for wavelengths longer than 1 m.

Line 14 etc: photometric bands

The next block gives one output line for each photometric band. A list of all supported photometric bands can be found in Table 8.1. The first two numbers on the line are the quoted magnitude and flux in jansky, the next two numbers are the actual magnitude and flux. The meaning of the words quoted and actual is the same as in the *IRAS* Explanatory Supplement. The quoted flux is computed from the continuum and the emission line contribution; it is the flux as it would be observed. The actual flux is the monochromatic flux at the effective wavelength of the photometric band; it is included for information only, since it is not an observable. It is useful however to assess the magnitude of the color correction factor and the line contribution for each photometric band. The conversion between magnitudes and fluxes is defined by the requirement that the quoted and actual flux are equal for a $F_\nu \sim \nu^{-1}$ spectrum with no line contribution.

The next number on the line is the contribution in percent of the line emission to the total in-band flux. Then follow the most important single emission lines that contribute to the in-band flux (up to three, only those contributing more than 0.5 % are given). For each emission line three things are given: the ionic species, the wavelength in Ångstrom ($\lambda < 10$ μm) or tenths of a micron ($\lambda \geq 10$ μm) and the contribution of this line in percent.

8.2.5 Additional optimizer output

The definition of the χ^2 of a model has been changed with respect to the original code and is now calculated in a non-standard manner. All the observables that are fitted in a model run are separated into five distinct categories. These categories are labeled 'spectrum' (sp), 'photometry' (ph), 'column dens' (cd), 'abs flux' (af) and 'ang diameter' (ad). We will now explain how the total χ^2 is calculated. First, the contribution χ_i^2 of the i-th observable to the total χ^2 is calculated as

$$\chi_i^2 = \left(\frac{F_i^{\rm m} - F_i^{\rm o}}{\min(F_i^{\rm m}, F_i^{\rm o})\,\sigma_i} \right)^2 ,$$

where $F_i^{\rm o}$ is the observed value for the i-th observable, $F_i^{\rm m}$ the model value for this observable and σ_i the relative error in the observed value. If the observable could only be observed as an upper limit, the following alternative formulation is used

$$\chi_i^2 = \left(\frac{\max(F_i^{\rm m}, F_i^{\rm o}) - F_i^{\rm o}}{F_i^{\rm o}\,\sigma_i} \right)^2$$

where $F_i^{\rm o}$ now stands for the upper limit. Second, for each of the five categories the *average* $\chi_{\rm c}^2$ is calculated using

$$\chi_{\rm c}^2 = \frac{\sum_{i=1}^{N} \chi_i^2}{N} \quad \text{for c} = \text{sp, ph, cd, af, ad}$$

Where N is the number of observables in that category. If a certain category is empty, the value for $\chi_{\rm c}^2$ is taken to be zero. Third, the total χ^2 of the model is calculated by adding all the averaged $\chi_{\rm c}^2$-values for each of the categories. We can write this as

$$\chi^2 = \chi_{\rm sp}^2 + \chi_{\rm ph}^2 + \chi_{\rm cd}^2 + \chi_{\rm af}^2 + \chi_{\rm ad}^2.$$

For each of the categories which is not empty a line of output is generated which gives the name of the category, the number of observables contained in it, the total χ^2 of all these observables and the average $\chi_{\rm c}^2$ computed from that. Finally, in Table 8.3 a summary is given of which observables belong to which category.

This is approach is chosen because normally many more line ratios are given than other types of observables. If no precautions would be taken, the fitting proces would be completely dominated by the line ratios and virtually no weight would be given to the other observations. Averaging over each of the categaries ensures that the dominance of the line ratios is diminished.

Table 8.3 — *Definition of the five optimizing categories used in* CLOUDY.

category	optimization command
spectrum	OPTIMIZE LINES (line ratios)
photometry	OPTIMIZE LINES (photometry)
	OPTIMIZE COLOR TEMPERATURE
	OPTIMIZE FAR-INFRARED FLUX
	OPTIMIZE FLUX ($1\ \mu\text{m} \leq \lambda \leq 300\ \mu\text{m}$)
column dens	OPTIMIZE COLUMN DENSITY
abs flux	OPTIMIZE LUMINOSITY
	OPTIMIZE INTENSITY
	OPTIMIZE FLUX ($\lambda < 1\ \mu$m or $\lambda > 300\ \mu$m)
ang diameter	OPTIMIZE DIAMETER

8.3 Additional emission lines

In the course of developing CLOUDY, many emission lines have been added to the code. These are mainly infrared lines of hydrogen and helium, but also some fine-structure lines of heavier elements have been added. A complete list of the lines is given in Table 8.4. This list however should be extended in the future. Probably the most important lines that still have to be added, are the infrared lines of He I.

8.4 References

Dopita M.A., Meatheringham S.J., 1990, ApJ 357, 140

Table 8.4 — *List of all the lines added to* CLOUDY*. The first two columns give the identifier used by* CLOUDY*, the third and fourth column give the standard spectroscopic notation and the last column the vacuum wavelength in micrometer.*

Cloudy identifier	Spectroscopic identification		λ μm	Cloudy identifier	Spectroscopic identification		λ μm
H 1f 930	H I	1–7	0.09307482	H 1f 382	H I	6–16	3.8194511
H 1f 926	H I	1–8	0.09262256	H 1f 1906	H I	7–8	19.061898
H 1f 3970	H I	2–7	0.39711950	H 1f 1131	H I	7–9	11.3086954
H 1f 3889	H I	2–8	0.38901506	H 1f 876	H I	7–10	8.7600641
H 1f 3835	H I	2–9	0.38364719	H 1f 751	H I	7–11	7.5081049
H 1f 3798	H I	2–10	0.37989757	H 1f 677	H I	7–12	6.7719905
H 1f 3771	H I	2–11	0.37717012	H 1f 629	H I	7–13	6.2919159
H 1f 3750	H I	2–12	0.37512174	H 1f 596	H I	7–14	5.9568435
H 1f 3734	H I	2–13	0.37354296	H 1f 571	H I	7–15	5.7114622
H 1f 3722	H I	2–14	0.37229966	H 1f 552	H I	7–16	5.5251882
H 1f 3712	H I	2–15	0.37130265	H 1f 2780	H I	8–9	27.803379
H 1f 3704	H I	2–16	0.37049064	H 1f 1620	H I	8–10	16.2091041
H 1f 10049	H I	3–7	1.00521281	H 1f 1238	H I	8–11	12.3871678
H 1f 9546	H I	3–8	0.95485899	H 1f 1050	H I	8–12	10.5034991
H 1f 9229	H I	3–9	0.92315474	H 1f 939	H I	8–13	9.3920177
H 1f 9015	H I	3–10	0.90173849	H 1f 866	H I	8–14	8.6645025
H 1f 8863	H I	3–11	0.88652168	H 1f 815	H I	8–15	8.1548905
H 1f 8750	H I	3–12	0.87528755	H 1f 778	H I	8–16	7.7803696
H 1f 8665	H I	3–13	0.86673983	H 1f 3886	H I	9–10	38.869866
H 1f 8598	H I	3–14	0.86007536	H 1f 2234	H I	9–11	22.340456
H 1f 8545	H I	3–15	0.85477304	H 1f 1688	H I	9–12	16.8806281
H 1f 8502	H I	3–16	0.85048188	H 1f 1418	H I	9–13	14.1830843
H 1f 217	H I	4–7	2.1661196	H 1f 1258	H I	9–14	12.5870767
H 1f 19445	H I	4–8	1.9450871	H 1f 1154	H I	9–15	11.5394914
H 1f 18174	H I	4–9	1.81790841	H 1f 1080	H I	9–16	10.8036015
H 1f 17362	H I	4–10	1.73668503	H 1f 5252	H I	10–11	52.534886
H 1f 16806	H I	4–11	1.68111115	H 1f 2983	H I	10–12	29.839500
H 1f 16407	H I	4–12	1.64116742	H 1f 2233	H I	10–13	22.3315740
H 1f 16109	H I	4–13	1.61137138	H 1f 1861	H I	10–14	18.6151505
H 1f 15880	H I	4–14	1.58848802	H 1f 1641	H I	10–15	16.4117243
H 1f 15700	H I	4–15	1.57049520	H 1f 1496	H I	10–16	14.9622556
H 1f 15556	H I	4–16	1.55606993	H 1f 6905	H I	11–12	69.071965
H 1f 465	H I	5–7	4.6537781	H 1f 3883	H I	11–13	38.842987
H 1f 374	H I	5–8	3.7405565	H 1f 2882	H I	11–14	28.8311497
H 1f 330	H I	5–9	3.2969916	H 1f 2386	H I	11–15	23.8680162
H 1f 304	H I	5–10	3.0392022	H 1f 2091	H I	11–16	20.9205615
H 1f 287	H I	5–11	2.8729959	H 1f 8873	H I	12–13	88.754631
H 1f 276	H I	5–12	2.7582676	H 1f 4947	H I	12–14	49.487676
H 1f 267	H I	5–13	2.67513124	H 1f 3646	H I	12–15	36.470508
H 1f 261	H I	5–14	2.61264766	H 1f 3000	H I	12–16	30.0100182
H 1f 256	H I	5–15	2.56432703	H 1f 11182	H I	13–14	111.856413
H 1f 253	H I	5–16	2.52609033	H 1f 6189	H I	13–15	61.910323
H 1f 1237	H I	6–7	12.371897	H 1f 4533	H I	13–16	45.340811
H 1f 750	H I	6–8	7.5024931	H 1f 13861	H I	14–15	138.65083
H 1f 591	H I	6–9	5.9082134	H 1f 7623	H I	14–16	76.247691
H 1f 513	H I	6–10	5.1286574	H 1f 16936	H I	15–16	169.41143
H 1f 467	H I	6–11	4.6725086	He2f 1085	He II	2–5	0.10849437
H 1f 438	H I	6–12	4.3764544	He2f 1025	He II	2–6	0.10252729
H 1f 417	H I	6–13	4.1707939	He2f 992	He II	2–7	0.09923635
H 1f 402	H I	6–14	4.0208675	He2f 972	He II	2–8	0.09721116
H 1f 391	H I	6–15	3.9075486	He2f 3203	He II	3–5	0.3204027

Table 8.4 — *Continued.*

Cloudy identifier		Spectroscopic identification		λ μm	Cloudy identifier		Spectroscopic identification		λ μm
He2f	2733	He II	3–6	0.27341061	He2f	558	He II	10–13	5.5806039
He2f	2511	He II	3–7	0.25119612	He2f	465	He II	10–14	4.6518788
He2f	2386	He II	3–8	0.23861309	He2f	410	He II	10–15	4.1012480
He2f	2306	He II	3–9	0.23069044	He2f	374	He II	10–16	3.7390294
He2f	10124	He II	4–5	1.0126385	He2f	1726	He II	11–12	17.260917
He2f	6560	He II	4–6	0.6561909	He2f	970	He II	11–13	9.706769
He2f	5412	He II	4–7	0.5413025	He2f	720	He II	11–14	7.2048345
He2f	4859	He II	4–8	0.4860676	He2f	596	He II	11–15	5.9645591
He2f	4542	He II	4–9	0.45428640	He2f	523	He II	11–16	5.2279972
He2f	4339	He II	4–10	0.43398911	He2f	2217	He II	12–13	22.179575
He2f	18637	He II	5–6	1.8641866	He2f	1236	He II	12–14	12.366855
He2f	11626	He II	5–7	1.1629601	He2f	911	He II	12–15	9.113894
He2f	9345	He II	5–8	0.9347499	He2f	750	He II	12–16	7.4994330
He2f	8237	He II	5–9	0.8239049	He2f	2794	He II	13–14	27.952665
He2f	7593	He II	5–10	0.7594844	He2f	1547	He II	13–15	15.471250
He2f	7178	He II	5–11	0.7179501	He2f	1133	He II	13–16	11.330565
He2f	309	He II	6–7	3.091692	He2f	3464	He II	14–15	34.64853
He2f	18743	He II	6–8	1.8748468	He2f	1905	He II	14–16	19.054130
He2f	14760	He II	6–9	1.4764419	He2f	4232	He II	15–16	42.33555
He2f	12813	He II	6–10	1.2816336	Na 3	73	[Na III]	$^2P^o_{3/2}$–$^2P^o_{1/2}$	7.3190
He2f	11673	He II	6–11	1.1676436	Na 4	90	[Na IV]	$^3P_2$–$^3P_1$	9.0391
He2f	10934	He II	6–12	1.0936607	Na 4	213	[Na IV]	$^3P_1$–$^3P_0$	21.290
He2f	476	He II	7–8	4.763507	Na 6	86	[Na VI]	$^3P_1$–$^3P_2$	8.613
He2f	283	He II	7–9	2.8260078	Na 6	143	[Na VI]	$^3P_0$–$^3P_1$	14.33
He2f	219	He II	7–10	2.1891127	Na 7	47	[Na VII]	$^2P^o_{1/2}$–$^2P^o_{3/2}$	4.675
He2f	18757	He II	7–11	1.8762520	Mg 7	55	[Mg VII]	$^3P_1$–$^3P_2$	5.504
He2f	16918	He II	7–12	1.6922992	Mg 7	90	[Mg VII]	$^3P_0$–$^3P_1$	9.033
He2f	15719	He II	7–13	1.5723301	Al 5	29	[Al V]	$^2P^o_{3/2}$–$^2P^o_{1/2}$	2.905
He2f	695	He II	8–9	6.947984	Al 6	36	[Al VI]	$^3P_2$–$^3P_1$	3.660
He2f	405	He II	8–10	4.0506090	Al 6	91	[Al VI]	$^3P_1$–$^3P_0$	9.116
He2f	310	He II	8–11	3.0955178	Al 8	37	[Al VIII]	$^3P_1$–$^3P_2$	3.69
He2f	262	He II	8–12	2.6247943	Al 8	58	[Al VIII]	$^3P_0$–$^3P_1$	5.85
He2f	235	He II	8–13	2.3470382	Al 9	20	[Al IX]	$^2P^o_{1/2}$–$^2P^o_{3/2}$	2.045
He2f	216	He II	8–14	2.1652342	S 9	13	[S IX]	$^3P_2$–$^3P_1$	1.2523
He2f	971	He II	9–10	9.713475	S 9	38	[S IX]	$^3P_1$–$^3P_0$	3.755
He2f	559	He II	9–11	5.582820	S 11	14	[S XI]	$^3P_1$–$^3P_2$	1.39274
He2f	422	He II	9–12	4.2184239	S 11	19	[S XI]	$^3P_0$–$^3P_1$	1.92012
He2f	354	He II	9–13	3.5443147	Ar11	6918	[Ar XI]	$^3P_2$–$^3P_1$	0.69175
He2f	314	He II	9–14	3.1454766	Ar11	26	[Ar XI]	$^3P_1$–$^3P_0$	2.619
He2f	288	He II	9–15	2.8836878	Ca 8	23	[Ca VIII]	$^2P^o_{1/2}$–$^2P^o_{3/2}$	2.3211
He2f	1312	He II	10–11	13.128335	Fe13	107	[Fe XIII]	$^3P_0$–$^3P_1$	1.07498
He2f	745	He II	10–12	7.456816	Fe13	108	[Fe XIII]	$^3P_1$–$^3P_2$	1.08009